Int J Life Cycle Assess (2014) 19:69–78
DOI 10.1007/s11367-013-0619-8

LCA FOR AGRICULTURE

Reducing methane on-farm by feeding diets high in fat may not always reduce life cycle greenhouse gas emissions

S. Richard O. Williams · Peter D. Fisher · Tony Berrisford · Peter J. Moate · Keith Reynard

Received: 11 April 2012 / Accepted: 28 June 2013 / Published online: 19 July 2013

Abstract
Purpose To consider whether feed supplements that reduce methane emissions from dairy cows result in a net reduction in greenhouse gas (GHG) intensity when productivity changes and emissions associated with extra manufacturing and management are included.
Methods A life cycle assessment was undertaken using a model farm based on dairy farms in Victoria, Australia. The system boundary included the creation of farm inputs and on-farm activities up to the farm gate where the functional unit was 1 L of fat and protein corrected milk (FPCM). Electricity and diesel (scaled per cow), and fertiliser inputs (scaled on farm size) to the model farm were based on average data from a survey of farms. Fertiliser applied to crops was calculated per area of crop. Animal characteristics were based on available data from farms and literature. Three methane-reducing diets (containing brewers grain, hominy or whole cotton seed) and a control diet (cereal grain) were modelled as being fed during summer, with the control diet being fed for the remainder of the year in all cases.
Results and discussion Greenhouse gas intensity (kg CO_2-eq/L FPCM) was lower than the control diet when the hominy (97 % compared with control) and brewers grain (98 %) diets were used but increased when the whole cottonseed diet was used (104 %). On-farm GHG emissions (kg CO_2-eq) were lower than the control diet when any of the methane-reducing diets were used (98 to 99.5 % of emissions when control diet fed). Diesel use in production and transport of feed supplements accounted for a large portion (63 to 93 %) of their GHG intensity (kg CO_2-eq/t dry matter). Adjusting fertiliser application, changing transport method, changing transport fuel, and using nitrification inhibitors all had little effect on GHG emissions or GHG intensity.
Conclusions Although feeding strategies that reduce methane emissions from dairy cows can lower the GHG emissions up to the farm gate, they may not result in lower GHG intensities (g CO_2-eq/L FPCM) when pre-farm emissions are included. Both transport distance and the effect of the feed on milk production have important impacts on the outcomes.

Keywords Carbon footprint · Dairy cows · Emissions intensity · Enteric methane · Feed supplements

Responsible editor: Barbara Nebel

S. R. O. Williams (✉) · P. J. Moate
Department of Primary Industries, Future Farming Systems Research Division, 1301 Hazeldean Road, Ellinbank, VIC 3821, Australia
e-mail: richard.williams@dpi.vic.gov.au

P. D. Fisher
Department of Primary Industries, Future Farming Systems Research Division, 255 Ferguson Rd, Tatura, VIC 3616, Australia

T. Berrisford
Department of Primary Industries, Farm Services Victoria, Cnr Fenwick and Little Malop, Geelong 3220, Australia

K. Reynard
Department of Primary Industries, Future Farming Systems Research Division, Cnr Midland Hwy and Taylor St, Epsom, VIC 3551, Australia

1 Introduction

In response to concerns about the influence of enteric methane on global warming, the possibility of using nutritional manipulation strategies to reduce enteric methane production by domesticated ruminants has become an important research area (e.g., Grainger et al. 2010; Moate et al. 2011). Increasing the fat concentration in the diet of cattle has been shown to reduce the methane emissions from those cattle (Martin et al. 2010; Moate et al. 2011). However, this dietary strategy can only be used when fat is naturally low in the base feed. In the temperate regions of Australia, pasture (the base feed) is low in fat during the summer months. It is not

known if reducing direct emissions using this dietary strategy also results in a net reduction in greenhouse gas (GHG) emissions across the value chain, from feed production to milk harvesting. Such an analysis, or life cycle assessment (LCA) approach, needs to include the emissions during production of the raw materials for the feed supplements, manufacture and distribution of the supplements, as well as any emissions that result from altering the management system. The ranking of mitigation strategies can change depending on whether the on-farm emissions only are considered or if the on-farm plus upstream supporting activities (such as grain production) are included (O'Brien et al. 2010).

Different dietary treatments may affect milk composition (e.g., Moate et al. 2011), which affects the energy density embodied in the milk. Using fat and protein corrected milk (FPCM) takes this effect into account by calculating the volume of milk of a standard composition that has the same energy density as the fresh milk obtained (IDF 2010).

We hypothesised that feed supplements that reduce methane emissions from dairy cows would not result in a net reduction in GHG intensity (kg CO_2-eq/L FPCM) when upstream emissions and productivity impacts were considered.

2 Methods

2.1 Problem definition

The goal of the investigation was to assess GHG mitigation due to dietary supplements from the perspective of the net emissions from cradle to farm gate. Two functional units were used to compare the results: (1) total GHG emissions from cradle to farm gate, and (2) GHG intensity of 1 L of FPCM (IDF 2010) at the farm gate.

On-farm activities and emissions associated with production and transport of major inputs were included within the system boundary (Fig. 1). Veterinary services, medications, and chemical purchases were all excluded as a previous (unpublished) study showed them to contribute less than 1 % of total emissions. Capital items, both land and machinery, were also excluded. The model farm was assumed to be in a steady state so no changes to land use were included.

The LCA study was undertaken using the calculation process described in the Australian National Greenhouse Accounts—National Inventory Report 2009 (DCCEE 2010). An attributional approach was used as suggested by the International Dairy Federation (IDF 2010). This approach is suitable when several static scenarios are being compared, rather than investigating how associated industries will change in response to the entire dairy industry switching to a particular feed supplement.

Allocation of emissions between co-products (milk and meat) used the default values of 85.6 % to milk and 14.4 % to meat from the physical causality method of the IDF (2010). An economic allocation method was also applied, for comparison.

2.2 Farm details

A model farm was simulated for the purpose of carrying out the LCA study. While this model is not based on a specific farm, it is based on data from farms and experiments so it

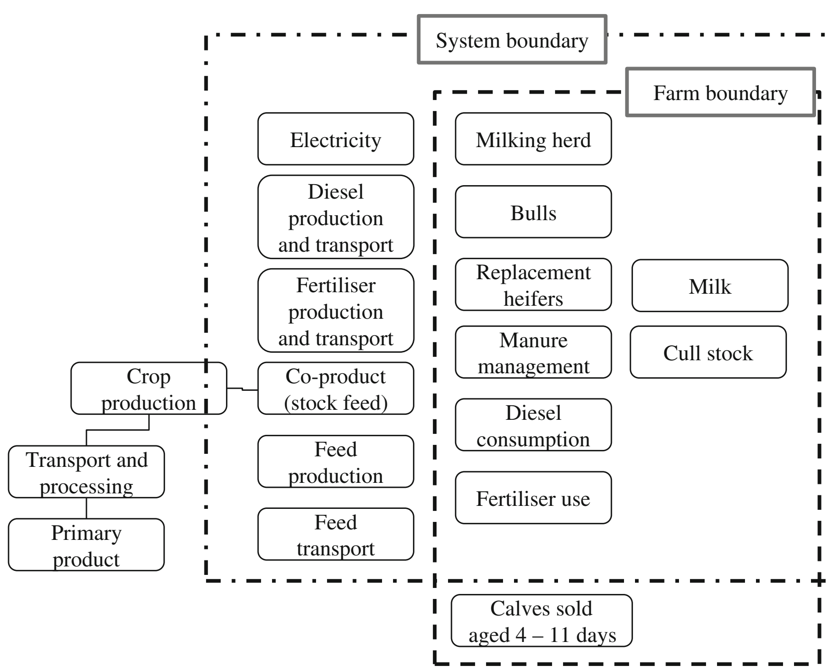

Fig. 1 Generic farm activities and major inputs were included in the investigation

provides a useful context for comparing the possible changes in GHG emissions when each of the methane-reducing diets is used. Farm area was taken as 180 ha with 5 % used for growing forage crops, based on a survey of non-irrigated dairy farms in Gippsland, Victoria, Australia (DPI 2010). Farm income (DPI 2010) for the modelled year was split across the sale of milk ($2,059/cow) and livestock ($153/cow). Number of milking cows was set at 350, with each cow producing 7,030 kg FPCM per year in the control scenario.

2.3 Farm energy

Electricity consumption was considered to be a function of the number of milking cows since more than 90 % of electricity use occurs within the dairy (Genesis Automation 2000). An increase in milking herd size results in longer milking duration or larger equipment being used, resulting in more electricity being consumed. Electricity consumption (DPI 2010) was plotted against farm size (expressed as the number of milking cows) and the resulting linear regression was forced through the origin (Fig. 2).

$$\text{Electricity use(kWh)} = 299.4(\pm 12.68) \times \text{No.of cows}, \quad R^2 = 0.97 \tag{1}$$

Diesel volume used was collated from a survey of dairy farms (DPI 2010) then estimated by (Eq. 2), derived from a linear regression (Fig. 2) of diesel use on dairy farms versus the number of cows. The GHG emissions from diesel were modelled in two parts, the pre-farm emissions from manufacture and delivery, and the on-farm emissions from use on farm.

$$\text{Diesel used(L)} = 25.8(\pm 2.44) \times \text{No.of cows}, \quad R^2 = 0.87 \tag{2}$$

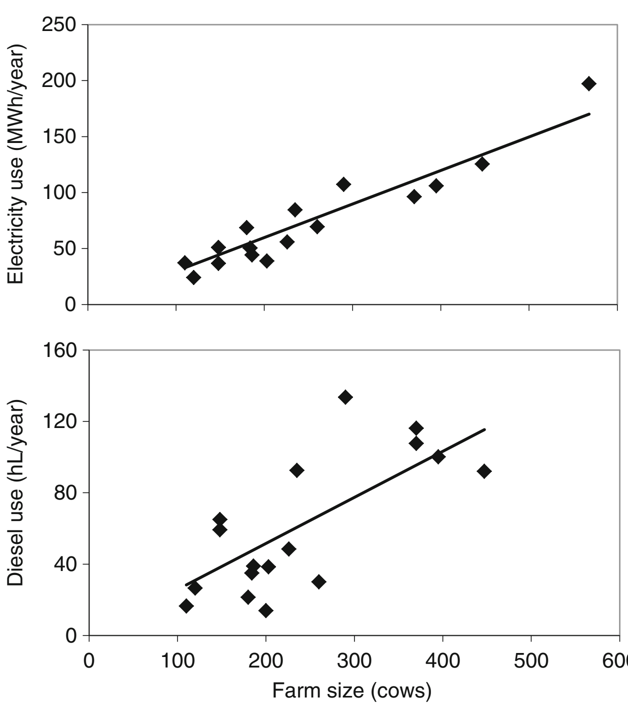

Fig. 2 Electricity consumption (*top*) and diesel use (*bottom*) were both related to farm size expressed as number of milking cows

2.4 Farm fertiliser

Fertiliser use was based on quantities reported for non-irrigated, Gippsland dairy farms (DPI 2010). Sixty-four different fertiliser blends were reported as used so all fertilisers were converted to the mass of N, P, K and S applied as a means of averaging this wide range. For fertiliser applied to pasture, there did not appear to be any trend with either the number of milking cows or the area of pasture for P, K or S despite pasture area ranging from 80 to 300 ha. Farm size was also expressed as number of cows multiplied by area (cow hectares) as either an increase in cows or increase in area was expected to require an increase in the amount of fertiliser applied. However, there was no trend with this parameter of farm size either. This could reflect farmers adjusting their fertiliser use in response to higher soil fertility on the surveyed farms. There was a trend for N applied but the correlation was poor. Therefore, a simple average, kilogram per cow hectare, was used (Table 1). For fertiliser applied to crops, there was a trend with area; so, linear regressions forced through zero were used to determine the rate of application of each nutrient (Table 1). Quantities applied to pasture were derived from non-irrigated, Gippsland dairy farms (DPI 2010). Quantities applied to crops were taken only from those farms where crops were grown (DPI 2010). Emissions of N_2O from fertiliser use were calculated using emissions factors (kg N_2O-N/kg N applied) of 0.004 for direct N_2O emissions from applied N, and 0.001 for N_2O emitted indirectly from volatilised N, and 0.0038 for N_2O from fertiliser N lost through leaching and runoff (DCCEE 2010). Fertiliser N is volatilised as NH_3 and oxides of N, which are subsequently deposited onto soil or water, where some N is released as N_2O.

Mass of urea required was determined by the mass of N required and an N concentration in urea of 460 g/kg. Mass of potassium chloride required was determined by the mass of

Table 1 Nutrients applied on non-irrigated farms in Gippsland

Nutrient	Pasture (kg/[cow.ha])	Crop (kg/ha)
N	0.421	113.3
P	0.052	28.7
K	0.119	26.8
S	0.063	9.2

K required and a K concentration in potassium chloride of 500 g/kg. Masses of single and triple super were calculated by solving the simultaneous equations:

$$S = SS \times SSupS + TS \times TSupS$$

$$P = SS \times SSupP + TS \times TSupP$$

Where:

SSupP	proportion of single super that is P, fraction, 0.086
SSupS	proportion of single super that is S, fraction, 0.110
TSupP	proportion of triple super that is P, fraction, 0.200
TSupS	proportion of triple super that is S, fraction, 0.008
SS	mass of single super required, in kilograms
TS	mass of triple super that is required, in kilograms
P	mass of P required, in kilograms
S	mass of S required, in kilograms

From the above equations for the mass of single super required (Eq. 3) and triple super required (Eq. 4) were derived.

$$SS = \frac{S - \dfrac{TSupS \times P}{TSupP}}{SSupS - \dfrac{TSupS \times SSupP}{TSupP}} \tag{3}$$

$$TS = \frac{P - SSupP \times SS}{TSupP} \tag{4}$$

2.5 Farm animals

Herd demographics (Table 2) were taken from Browne et al. (2011) as they collated data from multiple farms over multiple years. The body weight of milking cows was taken from Moate et al. (2011) to be consistent with the feed consumption and methane emissions, used in the LCA analysis, of those same cows. Body weight of bulls and replacement stock, and mass gain of all classes of animals were the default values from the Australian inventory (DCCEE 2010). Assumptions concerning stock were: replacement bulls were purchased at working age, all replacement heifers were raised on the farm without loss, and all other calves were sold within 11 days from birth. The resulting herd demographics were 350 milking cows, 88 heifers less than 1 year of age and 88 heifers greater than 1 year of age (each 25 % of the milking herd) and 4 bulls (1 % of milking herd) (Table 2). The milking herd was assumed to be static, so 88 cows either died or were sold each year.

Milk production was based on actual yields recorded at DPI Ellinbank from April 2010 to March 2011. Milk yield data were smoothed to generate seasonal production data and to remove fluctuations that may have been artefacts due to weather conditions within the data period. Milk yield during summer, when the supplements were fed, was dependent on the diet being fed (Table 3).

Manure management for the simulated farm was based on inventory average values for Victoria (DCCEE 2010), with 92 % of manure from milking cows being voided at pasture, and 100 % voided at pasture for other dairy cattle. The remaining 8 % from milking cows was assumed to be collected in a lagoon system. Excretion rates were calculated using the Australian inventory equations (DCCEE 2010). The inventory calculations use an integrated methane conversion factor in the calculation of methane emissions from manure to allow for the fraction of voided solids that is converted to methane. For a pasture plus lagoon system, this conversion factor was calculated to be 8.1 %. This factor was used instead of the Australian inventory (DCCEE 2010) figure of 6.5 %, which is based on a state average data and includes lagoon, slurry, and spreading systems.

Table 2 Quantities, mass and rate of bodyweight gain for the stock used in the model

Stock	Quantity	Mass (kg)	Mass gain (kg/day)
Milking cows	350 (= n)[a]	600[b]	0.04[c]
Heifers <1 year	25 % of n[a]	250[c]	0.1[c]
Heifers >1 year	25 % of n[a]	450[c]	0.6[c]
Bulls, mature	1 % of n[a]	600[c]	0.5[c]

[a] Browne et al. (2011)

[b] Moate et al. (2011)

[c] DCCEE (2010)

Table 3 Composition of the diets (g/kg DM) used in summer and the resulting methane yield (g/kg DM intake) and fat and protein corrected milk (FPCM, kg/cow per day)

Diet	Control [a]	BG [a]	Hominy[a]	WCS[b]
Lucerne hay	254	265	255	259
Pasture silage	373	370	377	407
Cracked wheat	303	106	0	173
Brewers grain	0	259	0	0
Hominy meal	0	0	270	0
Whole cottonseed	0	0	0	160
Methane yield	25.0	23.7	22.1	23.5[c]
FPCM	24.4	24.0	24.6	21.4

BG brewers grain (barley), *WCS* whole cottonseed

[a] Moate et al. (2011)

[b] Grainger et al. (2010)

[c] Corrected data scaled relative to control diet shown

2.6 Feeding strategies

In the control scenario, the primary feed source for all animals in the model was grazed pasture. Each milking cow was also given 7.5 kg DM wheat/day during lactation (Browne et al. 2011). Any feed gaps were filled with previously conserved, surplus pasture. This diet was fed in autumn, winter and spring. In summer, four different diets were compared (1) Control: wheat and forage; (2) Brewers grain, wheat and forage, (3) Hominy meal and forage and (4) Whole cotton seed, wheat and forage. The forage during summer was pasture silage grown and conserved on farm during spring, and purchased lucerne hay (Table 3).

Daily intake during summer (20.9 kg DM/cow) was set the same for all four diets and was estimated using the inventory equation, which is based on feed intake of non-lactating cattle plus an additional intake for milk production (DCCEE 2010). Diet composition and the resulting enteric methane emissions and milk yields for each of the four diets during summer was taken from the experiments of Moate et al. (2011) and Grainger et al. (2010) (Table 3). Grainger et al. (2010) acknowledged their reported methane emissions were higher than other data and determined a correction so their corrected values were used. To ensure the results of the two different experiments were comparable, the methane emission from cows fed whole cotton seed was expressed as a fraction of that from cows fed the control diet (Grainger et al. 2010). This fraction was then applied to the methane emissions from cows fed the control diet in the experiment of Moat et al. (2011) to estimate the methane emission from cows fed whole cotton seed relative to the methane emissions measured in the experiment of Moate et al. (2011). For autumn, winter and spring, when methane-reducing supplements were not provided, daily intake (kg DM/cow), diet composition, and enteric methane were estimated using the inventory equations (DCCEE 2010).

Milk yield was adjusted for the months when the dietary strategies were used. Adjustment was relative to the control, with milk yields being scaled relative to the fat and protein content of the milk reported in the results of Moate et al. (2011) and Grainger et al. (2010). Fat and protein corrected milk (IDF 2010) was used because it adjusts for any differences in milk composition between dietary strategies.

2.7 Supplementary feed

Allocation of emissions to each of the supplementary feeds was done on an economic basis, as recommended by the IDF (2010). Lucerne hay was purchased and delivered in large rectangular bales. Establishment of the lucerne was excluded from the emissions calculation. Maintenance (Pritchard and Dettmann 2011) and harvesting (Frank Mickan, personal communication) of lucerne was included. Silage was produced from pasture grown on the farm, so production is already included as part of the farm inputs.

Production of wheat grain was modelled using the "Wheat at farm/AUS" process from the Australasian library in SimaPro (Centre for Design at RMIT and Life Cycle Strategies Pty Ltd 2010). Additional processes included in the emissions calculation were transport to the feed mill (400 km, 73 % rural travel, 30 on 45 t truck with tare of 21 t, no backhaul), cracking of the grain (1.5 kWh electricity per tonne processed, loss rate 0.5 % of incoming grain) and transport to the dairy farm (50 km, rural travel, 28 on 30 t truck with tare of 15 t, no backhaul).

The production of barley, the source grain for brewers grain (BG), was modelled by including the inputs for paddock preparation, sowing, weed control, fertiliser application, and harvesting (APVMA 2011; Bashford 1999; Case 2011; DAF 2011; Hoy 2008). Emissions from the activities resulting from beer production at the brewery and transport of grain to the brewery were fully allocated to beer, making it unnecessary to model the brewery for this study. Emissions that contributed to the grain production were allocated between beer and BG on an economic basis. Transport of BG from the brewery to the dairy farm (150 km, 70 % rural travel, 28 on 30 t truck with tare of 15 t, no backhaul) was fully allocated to the BG. The GHG emissions of the barley leaving the farm gate was allocated 98.4 % to beer and 1.6 % to BG using $4/L for beer and $300/t for BG as a stock feed. Every 1 L of beer was accompanied by the production of 0.22 kg DM of BG (Hospido et al. 2005; Koroneos et al. 2005; Talve 2001) and consumed 0.26 kg of barley grain (The Climate Conservancy 2008; Cordella et al. 2008; Koroneos et al. 2005).

Hominy meal is a by-product from the dry milling of maize grain and consists of the germ plasm, skins and some grits. The production of maize was modelled using the average inputs required to produce 1 t of maize grain in Australia. These were land area, irrigation water, fertiliser, pesticide and diesel. Quantities of inputs for irrigated maize were taken from CSD (2008) while those for dryland maize were compiled from information supplied by Kieran O'Keeffe and Robert Eveleigh (personal communications). Composition of the fertilisers used was taken from Incitec Pivot (2011). The production share for irrigated maize was 80 % and dryland maize was 20 % (Robert Eveleigh, personal communication). Fraction of stubble burnt was taken as 50 % (Grant and Beer 2006). Of the maize grain entering the mill, 72 % left as grit for further processing and 28 % was hominy meal (Gerard Toskin, personal communication). Transport of the maize grain to the mill and all emissions associated with the milling were allocated to the maize grit, thus making it unnecessary to model the mill in this study. Transport of hominy from the mill to the dairy farm (900 km, 85 % rural travel, 28 on 30 t truck with tare of 15 t, backhaul 1 load in 5)

was allocated to the hominy meal. The GHG emissions of the maize grain entering the mill was allocated between the grit and hominy on an economic basis using values per tonne of $775 for grit and $218 for hominy.

Whole cotton seed (WCS) production was modelled using the fertiliser, diesel and pesticide inputs of cotton (CSD 2008, Robert Eveleigh personal communication). As with the other feed supplements, transport from the farm to the gin and all inputs to and emissions from the gin were assigned to cotton lint, making it unnecessary to model the gin in this study. Transport of WCS from the gin to the model farm (1,700 km, 95 % rural travel, 28 on 30 t truck with tare of 15 t, backhaul 1 load in 5) was assigned to the WCS. Each bale of cotton delivered to the gin was 40 % cotton, 58 % WCS, and 2 % trash. Allocation of GHG emissions associated with cotton seed production up to the farm gate was done on an economic basis using values of $2,200/t for cotton lint, $250/t for WCS, and $0/t for trash.

2.8 Calculations

SimaPro was used to model the GHG emissions from a model farm when cows were fed wheat, brewer grain, hominy meal or whole cottonseed. Life cycle inventory data for transport, energy, fertiliser and wheat processes were obtained from the Australasian library (Centre for Design at RMIT and Life Cycle Strategies Pty Ltd 2010). Calculations of on-farm emissions were constructed using equations and emission factors from the Australian National Greenhouse Accounts methodology (DCCEE 2010). Processes for feeds other than wheat were constructed using information from industry reports, agronomy practices and published LCA studies.

Calculations of emissions were grouped by source material (e.g., fertiliser) rather than location of emission (e.g., soil or air). This was for convenience since many derived values fed into subsequent calculations. Processes were taken from the EcoInvent library (ecoinvent Centre 2007) when no other suitable process or information was available. The global warming potential (GWP, 100-year basis) of 1 kg of CH_4 was taken as 21 kg CO_2-eq and 1 kg of N_2O as 310 kg CO_2-eq as per DCCEE (2010).

3 Results

Annual GHG emissions on-farm, relative to the control diet, were similar or reduced when the BG (0.5 % less than control), hominy (2.0 % less) and WCS (1.0 % less) were fed in summer. Pre-farm emissions were reduced relative to the control diet when the BG (5.6 % less than control) and hominy (7.7 % less) diets were fed in summer but increased when the WCS diet (3.0 % more than control) was fed. This resulted in total emissions to the farm gate being less than the control diet when the BG (1.6 % less) and hominy (3.2 % less) diets were fed in summer. Total emissions to the farm gate when WCS was fed in summer were similar to when the control diet was fed.

Greenhouse gas intensity (kg CO_2-eq/L FPCM) when the WCS supplement was used was 4.4 % higher than when the control diet was fed. This change in ranking was due to a 12 % reduction in milk yield when this supplement was fed (Table 4). Both the BG and hominy diets resulted in reduction in GHG intensity similar to the reductions in total GHG emissions.

The carbon footprint of the wheat, delivered to the dairy farm, was 425 kg CO_2-eq/t DM, most (80 %) of which was associated with its production, of which tractor diesel use accounted for about one third (36.4 % of total footprint). Total diesel use, which includes production plus transport,

Table 4 Annual greenhouse gas emissions resulting from the summer dietary strategies

Diet	GHG emissions (t CO_2-eq)			GHG intensity[d] (kg CO_2-eq/L FPCM[e])	
	On-Farm[a]	Pre-Farm[b]	Total[c]	IDF	Economic
Control (inventory)	1,980	568	2,548	0.89	0.96
Control	2,030	568	2,598	0.90	0.98
Brewers grain	2,020	536	2,556	0.89	0.97
Hominy	1,990	524	2,514	0.87	0.95
Whole cotton seed	2,010	585	2,595	0.94	1.02

[a] On-farm includes only those emissions occurring within the physical boundary of the farm

[b] Pre-farm includes the emissions associated with all purchased items such as feed and energy

[c] Total includes all emissions up to the farm gate

[d] Greenhouse gas intensity is shown using the allocation method of the International Dairy Federation (IDF) and economic allocation

[e] Fat and protein corrected milk

accounted for 55 % of the GHG emissions for wheat delivered to the dairy farm.

The carbon footprint of the BG, delivered to the dairy farm, was 129 kg CO_2-eq/t DM. Transport was the single largest (93.3 %) contributor to this. The high water content (80 %) of the BG contributed to the high transport emissions to deliver 1 t DM, but the primary reason is the small proportion of production emissions allocated to the BG as a result of its low economic value relative to beer, the primary product. Total diesel use, transport plus production, accounted for 99 % of the total footprint of BG.

The carbon footprint of the hominy, delivered to the dairy farm, was 231 kg CO_2-eq/t DM. More than half of this was generated by transport because hominy was assumed to be transported 900 km. When diesel use during maize production was added, total diesel use accounted for 63 % of the total GHG emissions.

The carbon footprint of the WCS, delivered to the dairy farm, was 497 kg CO_2-eq/t DM. Approximately half of this was associated with its production and half with its transport. A large portion of the GHG emissions from the production of WCS was from the use of diesel in the growing of cotton. Total diesel use accounted for almost 80 % of the carbon footprint of delivered WCS.

4 Discussion

4.1 Greenhouse gas emissions

Contrary to our hypothesis, feed supplements that reduced methane emissions from lactating cows did result in a net reduction of GHG intensity (kg CO_2-eq/L FPCM) when brewers grain or hominy diets were fed during summer but there was a small increase when WCS was fed. The key reasons for this are the different reductions in methane emissions on-farm for each diet, differences in pre-farm emissions for each diet and changes in milk production when cows were fed each diet. The WCS was freighted 1,700 km so distance was a large contributor to the total emissions for that diet. Also, in the data set used here, the milk yield from WCS-fed cows (Grainger et al. 2010) was lower than that of control diet-fed cows although Dayani et al. (2011) and Miller et al. (2009) substituted WCS into a control diet and found no difference in milk yield. Total emissions when the WCS diet was fed were similar to when the control diet was fed, so if milk yield had been similar, then the GHG intensity would have been similar at 0.90 kg CO_2-eq/L FPCM.

The GHG intensity (kg CO_2-eq/L FPCM) using the IDF allocation method for all four diets was similar to, but lower than, comparable values from grass-based farms reported by Flysjö et al. (2011a) (1.0-kg CO_2-eq/L energy corrected milk) and O'Brien et al. (2011) (1.1-kg CO_2-eq/kg milk). Other reported values of GHG intensity from dairy systems were higher ranging from 1.1-kg CO_2-eq/L energy corrected milk (Flysjö et al. 2011a) to 1.6-kg CO_2-eq/L FPCM (Thomassen et al. 2008), but these included some indoor housing of animals during the colder times of the year whereas our cows were outdoors all year. The difference between our results and the results from other grass-based systems disappeared when the most recently published values of GWP (25 kg CO_2-eq for 1 kg of methane and 298 kg CO_2-eq for 1 kg of N_2O, Forster et al. 2007) were used in our assessment. The increase in GHG intensity is due to the increase in the impact of methane from livestock (about 70 % of all emissions as CO_2-eq) being larger than the reduction in impact from the use of nitrogenous fertilisers. Regardless of this change in impact, the ranking of feeding strategies remained unchanged, meaning our choice of GWP did not affect our comparison of dietary strategies.

Comparison of the carbon footprint for the feed supplements was difficult. As identified by Flysjö et al. (2011a), different researchers use different boundaries and factors when calculating the GHG emissions of products. The different environments, production practices, and local emission factors used in different studies meant direct comparisons to published results were not possible. Lechón et al. (2005) reported carbon footprints of 154-kg CO_2-eq/t for wheat and 143-kgCO_2-eq/t for barley in Spain. Eady et al. (2012) reported footprints of 253-kg CO_2-eq/t for wheat and 211-kg CO_2-eq/t for barley when sourced from a mixed-farming system in Western Australia. In contrast, we estimated carbon footprints of 301-kg CO_2-eq/t for wheat at source farm and 109-kg CO_2-eq/t for malting barley when grown in Victoria, Australia. Feng et al. (2010) reported the carbon footprint for maize grown in Iowa, United States, ranged from 262 to 360 kg CO_2-eq/t. These values are higher than the 248-kg CO_2-eq/t calculated by us and would have the effect of making the emissions from the hominy diet higher than calculated. A published carbon footprint for cotton seed could not be found.

4.2 Allocation

The allocation between milk and meat production was the method of the IDF (2010) and this seems a reasonable simplification based on the findings of Flysjö et al. (2011b). After comparing a range of allocation scenarios, they reported that the physical causality method of the IDF (2010), with an 86 % allocation to milk, was closest to the 76 % allocation to milk from a complete system expansion. Their economic allocation assigned 94 % of the farm carbon emissions to milk, which is similar to the 93 % economic allocation to milk used in our work.

None of the emissions from the factory processes that created each by-product were included in this study as all these emissions were allocated to the primary product. If the model allocated some of the processing emissions to a by-product, then the carbon footprints of the BG, WCS and hominy meal would be higher than those reported. This means the calculated net reduction in GHG emissions when the methane-reducing diets were fed may be eliminated. Complete modelling would be necessary to determine the actual change to the carbon footprints calculated. However, based on brewery emissions of 0.16-kg CO_2-eq/L beer (Berners-Lee 2010) and allocation between beer and BG, including the brewery is only likely to add approximately 12-kg CO_2-eq/t DM to the carbon footprint of the BG diet, an increase of 0.2 %.

4.3 Maximising supplement use

Adjusting diets to maximise the fat content was investigated as a means to increase the reduction of enteric methane. The fat content of the WCS diet was already at the upper limit of 60 g/kg DM for maintaining rumen function, and hence energy supply of lactating cows. However, there was opportunity to increase the fat concentration of the hominy diet, but this could only be done at the cost of reducing the protein concentration of the diet to a level below than necessary to meet cow requirements (Freer et al. 2007). In the BG diet, fat could be increased to 57 g/kg DM, an increase of 10 g/kg DM, by including more BG and using less wheat. Using the prediction equation of Moate et al. (2011), the methane emission from the milking cows on the increased BG diet was calculated to be 21.9 g/kg DM. The resulting annual total emissions were estimated as 2,528-t CO_2-eq, a reduction of 70-t CO_2-eq relative to the control diet. Although this provides a potential improvement in the BG supplement diet, there is a need to consider other constraints such as the quantity of BG the cows can eat and any change in N_2O emissions from the additional N in the reformulated diet, before claiming that increasing BG in the diet is advantageous.

4.4 Reduction options

Adjusting fertiliser purchases in response to the different nutrient concentration of each feeding strategy could be one way to reduce the carbon footprint of milk at the farm gate. Purchasing wheat (N concentration of 24 g/kg) as part of the control diet imports less N than purchasing WCS (N concentration of 36 g/kg) as part of the WCS diet. Over the summer period, this difference is equivalent to 3.4 t of urea. Since feeding the WCS diet brings more N onto the farm than the control diet, less urea could be purchased to fertilise pasture, with a saving of 3 t CO_2-eq. However, when compared to the 2,500-t CO_2-eq of GHG emissions for the whole farm, this potential reduction is negligible.

Increasing the longevity of milking cows from four to five lactations reduced the carbon footprint for the farm on the control diet to 2,530-t CO_2-eq or 0.88 kg CO_2-eq/L FPCM. This reduction is half that achieved by feeding hominy meal and is achieved by reducing the number of young stock reared each year as replacements for the milking herd. Further increasing the longevity of the milking cows will further reduce the total emissions of the farm. This reduction is in addition to any achieved through dietary strategies.

Road freight accounted for 19 % of the emissions for the supply of wheat to the dairy farm and 57 % of that for hominy. While this reflects the distance from the place of production to the dairy farm, it is also a function of the mode of transport used. For travel in rural areas, the trucks used had GHG emissions of 0.125-kg CO_2-eq/tonne km (tkm), but bulk transport by rail is only one tenth of this at 0.0124-kg CO_2-eq/tkm (Centre for Design at RMIT and Life Cycle Strategies Pty Ltd 2010). If WCS was freighted by rail for 90 % of the total distance, then by truck to the dairy farm, the GHG emissions from transport would be reduced by 75 %, with the total emissions of delivered WCS being reduced by 34 %. Similarly, if hominy was freighted by rail for 80 % of the total distance, the GHG from transport would be reduced by 70 %, with the total emissions of delivered hominy being reduced by 40 %. Both wheat and BG had much smaller travel distances, but at least half of their journey could be by rail, suggesting that a 45 % reduction in GHG emissions from transport could be possible. Despite these large reductions in the emissions from transport, using rail to transport the feeds would only result in about a 1 % reduction in the total emissions to the farm gate and the GHG intensity of the milk. This small reduction is due to the purchased feeds contributing only a small proportion (1.6 % for hominy to 11.5 % for wheat) to the total emissions of the farm, which are driven primarily by emissions from livestock (~70 % of total).

The "total fuel cycle" of a range of diesel alternatives were analysed by Meyer et al. (2011). They reported that compressed natural gas (CNG) has 95 % of the GHG emissions (in grams per tonne kilometre) of ultra low sulphur diesel. This is similar to the 8 % reduction for CNG relative to diesel reported by Beer et al. (2002). This small reduction in GHG emissions suggests that replacing diesel with CNG will not have a large effect on the carbon footprint of feed supplements as delivered, even in those cases where transport is about half of the footprint.

Nitrification inhibitors have been shown to reduce the loss of N from the soil as N_2O, but with responses estimated to range from 30 to 60 % (de Klein and Eckard 2008). In wheat, BG and WCS, fertiliser accounts for only a small proportion of the total emissions of delivered product, but for hominy,

N_2O emissions account for 18 %. If nitrification inhibitors were used on the maize crop, and reduced the loss of N as N_2O by 50 %, then the emissions of 1 t DM of delivered product would be reduced by 9 % for hominy. The resulting effect on the emissions of the model farm would be a 0.1 % reduction for the hominy diet.

4.5 Sensitivity to transport distance

A break-even distance was defined as the distance a supplement can be transported such that the total emissions to the farm gate are the same as the control diet. When looking at the annual carbon emissions to the farm gate, the break-even distance for BG was 443 km, for hominy, it was 4,106 km, and with WCS, it was 1,917 km, all of which are greater than the distances used in the farm simulation. In terms of emissions per litre FPCM, the break-even distance for BG was 359 km, for hominy, it was 4,259 km, and for WCS, it was 0 km. The differences between the break-even distances for whole farm versus per litre FPCM emissions reflect the effect of the supplement on milk yield. In the experiment of Grainger et al. (2010), WCS reduced milk yield such that transporting WCS any distance always gave more emissions per litre FPCM than the control diet.

4.6 Uncertainty

Three parameters of the many used in life cycle assessments have been reported to have the greatest impact on results (Flysjö et al. 2011a). For grazing dairy cattle, these are the emission factors for N_2O from excreta, fertilisers, and applied manure; the emission factor for methane from enteric fermentation of feed; and the feed intake of cattle. In our assessment, feed intakes and methane emissions were measured, which reduced the uncertainty surrounding them. Although all three parameters may affect the absolute values reported, they do not affect the ranking of the dietary strategies since the emission factor for N_2O was constant for all strategies and the measurements of methane emission and feed intake were all relative to the control diet.

There is some uncertainty around the electricity, diesel and fertiliser use since data were taken from only 20 farms. We chose to use detailed information from a few farms in preference to broad information from many farms to ensure strong links between the data from different farm activities were maintained.

We are confident that the methane emissions from the milking herd do reflect the relative differences for the dietary strategies investigated. However, we acknowledge that the data were taken from a small experimental herd and may not reflect the actual emissions if all cows in Victoria, Australia, were fed the experimental diets.

Transport often contributed a large portion of the carbon footprint of the feed supplements. While the distances used within the investigation are representative for a farm in Gippsland, different distances will need to be used if the investigation was repeated in a different dairying region.

Deaths of replacement stock were considered to be zero. While there are some losses in reality, our results are unaffected by this since the replacement animals contributed only a small portion of the total GHG emissions from the farm. Calves sold at 4 to 11 days of age were excluded from the study but with negligible impact on the results. Calves of this age do not have functioning rumens so there is no fermentation of feed and no generation of methane. Also, manure from these animals is a tiny proportion of annual manure production for the farm.

5 Conclusions

Although feeding strategies that reduce methane emissions from dairy cows can lower the direct GHG emissions from a farm, they may not result in lower total GHG emissions nor lower GHG intensities (g CO_2-eq/L FPCM) when pre-farm emissions are included. Both transport distance and the effect of the feed on milk production have important impacts on the outcomes. Further work is recommended to ensure the result of this research is not an artefact of the information used.

Acknowledgments This study was undertaken through funding from the Department of Primary Industries' Future Farming Systems Research Division. The suggestions and feedback provided by Richard Eckard are greatly appreciated.

References

APVMA (2011) Public chemical registration information system. http://services.apvma.gov.au/PubcrisWebClient/welcome.do. Accessed 20 June 2011

Bashford LL (1999) Nebraska OECD tractor test 1761—Summary 275. Case IH MX 270 Diesel, 18 speed, Agricultural Research Division, Institute of Agricultural and Natural Resources, University of Nebraska. Lincoln, Lincoln

Beer T, Grant T, Williams D, Watson H (2002) Fuel-cycle greenhouse gas emissions from alternative fuels in Australian heavy vehicles. Atmos Environ 36:753–763

Berners-Lee M. (2010) How bad are bananas? The carbon footprint of everything. Profile Books Ltd

Browne NA, Eckard RJ, Behrendt R, Kingwell RS (2011) A comparative analysis of on-farm greenhouse gas emissions from agricultural enterprises in south eastern Australia. Anim Feed Sci Technol 166–167:641–652

Case IH (2011) Specification catalogues for Patriot 3330 sprayer and axial-flow combines from http://www.caseih.com/australia/Pages/Home.aspx. Accessed 26 May 2011

Centre for Design at RMIT and Life Cycle Strategies Pty Ltd (2010) Australian LCI database version 2010.5, data released in SimaPro LCA Software. Life Cycle Strategies, Melbourne
Cordella M, Tugnoli A, Spadoni G, Santarelli F, Zangrando T (2008) LCA of an Italian lager beer. Int J Life Cycle Assess 13(2):133–139
CSD (2008) Summer crops—gross margin analysis. Cotton Seed Distributors, Wee Waa, NSW, Australia
DAF (2011) Barley nutrition. Department of Agriculture and Food, Western Australia, Perth, Australia http://www.agric.wa.gov.au/PC_92013.html?s=0. Accessed 26 May 2011
Dayani O, Ghorbani GR, Esmailizadeh AK (2011) Supplementation with whole cottonseed changes milk composition and milk fatty acid profile in dairy cows. Anim Prod Sci 51:95–101
DCCEE (2010) Australian national greenhouse accounts. National Inventory Report 2008 Volume 1. The Australian Government Submission to the UN Framework Convention on Climate Change May 2010. Department of Climate Change and Energy Efficiency, Canberra, Australia
de Klein CAM, Eckard RJ (2008) Target technologies for nitrous oxide abatement from animal agriculture. Aus J Exp Agric 48:14–20
DPI (2010) Dairy Industry Farm Monitor Project—2009/10. Department of Primary Industries, Melbourne, Victoria, Australia
Eady S, Carre A, Grant T (2012) Life cycle assessment modelling of complex agricultural systems with multiple food and fibre co-products. J Cleaner Prod 28:143–149
ecoinvent Centre (2007) ecoinvent data version 2.0, reports No. 1–25, as implemented in SimaPro 7.2. Swiss Centre for Life Cycle Inventories, Dübendorf
Feng H, Rubin OD, Babcock BA (2010) Greenhouse gas impacts of ethanol from Iowa corn: life cycle assessment versus system wide approach. Biomass Bioenerg 34:912–921
Flysjö A, Henriksson M, Cederberg C, Ledgard S, Englund J (2011a) The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. Agric Syst 104:459–469
Flysjö A, Cederberg C, Henriksson M, Ledgard S (2011b) How does co-product handling affect the carbon footprint of milk? Case study of milk production in New Zealand and Sweden. Int J Life Cycle Assess 16:420–430
Forster P et al (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S et al (eds) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 129–234
Freer M, Dove H, Nolan JV (eds) (2007) Nutrient requirements of domesticated ruminants. CSIRO Publishing, Collingwood, Victoria, Australia
Automation G (2000) Energy surveys of selected Victorian dairy farms. A report to Bonlac Foods and Sustainable Energy Authority. Genesis Automation, Hartwell, Victoria, Australia
Grainger C, Williams R, Clarke T, Wright A-DG, Eckard RJ (2010) Supplementation with whole cottonseed causes long-term reduction of methane emissions from lactating dairy cows offered a forage and cereal grain diet. J Dairy Sci 93:2612–2619
Grant T, Beer T (2006) Life-cycle assessment of greenhouse gas emissions from irrigated maize: The life-cycle analysis. In '6th Australian Maize Association Conference, 21–23 February 2006' Maize Association of Australia: Griffith, NSW, Australia
Hospido A, Moreira MT, Feijoo G (2005) Environmental analysis of beer production. Int J Agric Resour Gov Ecology 4(2):152–162
Hoy RM (2008) Nebraska OECD tractor test 1909—Summary 577. Case IH Steiger 430 Diesel, also Case IH STX 430 Diesel, also Case IH Steiger 435 Diesel 16 speed, Agricultural Research Division, Institute of Agricultural and Natural Resources. University of Nebraska, Lincoln
IDF (2010) A common carbon footprint approach for dairy, The IDF guide to standard lifecycle assessment methodology for the dairy sector. Bulletin 445/2010 of the International Dairy Federation. International Dairy Federation. Brussels, Belgium
Incitec Pivot (2011) Granulok Starter Z. Incitec Pivot Limited, Southbank, Victoria, Australia. http://www.incitec.com.au/zone_files/PDFs/GranulockBrochure1.pdf. Accessed 6 June 2011
Koroneos C, Roumbas G, Gabari Z, Papagiannidou E, Moussiopoulos N (2005) Life cycle assessment of beer production in Greece. J Cleaner Prod 13(4):433–439
Lechón Y, Cabal H, Sáez R (2005) Life cycle analysis of wheat and barley crops for bioethanol production in Spain. Int J Agric Resour Gov Ecology 4:113–122
Martin C, Morgavi DP, Doreau M (2010) Methane mitigation in ruminants: from microbe to the farm scale. Animal 4:351–365
Miller WF, Shirley JE, Titgemeyer EC, Brouk MJ (2009) Comparison of full-fat corn germ, whole cottonseed, and tallow as fat sources for lactating dairy cattle. J Dairy Sci 92:3386–3391
Moate PJ, Williams SRO, Grainger C, Hannah MC, Ponnampalam EN, Eckard RJ (2011) Influence of cold-pressed canola, brewers grains and hominy meal as dietary supplements suitable for reducing enteric methane emissions from lactating dairy cows. Anim Feed Sci Technol 166–167:254–264
Meyer PE, Green EH, Corbett JJ, Mas C, Winebrake JJ (2011) Total fuel-cycle analysis of heavy-duty vehicles using biofuels and natural gas-based alternative fuels. J Air Waste Manag Assoc 61:285–294
O'Brien D, Shalloo L, Grainger C, Buckley F, Horan B, Wallace M (2010) The influence of strain of Holstein–Fresian cow and feeding system on greenhouse gas emissions from pastoral dairy systems. J Dairy Sci 93:3390–3402
O'Brien D, Shalloo L, Patton J, Buckley F, Grainger C, Wallace M (2011) The effect of methodology on estimates of greenhouse gas emissions from grass-based dairy systems. Agric Ecosyst Environ 141:39–78
Pritchard & Dettmann (2011) Lucerne Agronomy Checklist. Pritchard & Dettmann, Kyneton, Victoria, Australia http://www.crtkyneton.com.au/lucerneagronomy.htm Accessed: 18 May 2011
Talve S (2001) Life cycle assessment of a basic lager beer. Int J Life Cycle Assess 6(5):293–298
The Climate Conservancy (2008) The carbon footprint of Fat Tire® amber ale. The Climate Conservancy, Palo Alto, California, United States
Thomassen MA, Dalgaard R, Heijungs R, de Boer I (2008) Attributional and consequential LCA of milk production. Int J Life Cycle Assess 13:339–349